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Gyorfi

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(54) **SYSTEMS AND METHODS FOR SPEED ESTIMATION BASED ON STRIDE DATA USING PREDICTIVE MODELING**

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G06F 17/10	(2006.01)
G01C 21/16	(2006.01)
G01C 22/00	(2006.01)

(52) **U.S. Cl.**

CPC ***G06F 17/10*** (2013.01); ***G01C 21/165*** (2013.01); ***G01C 22/006*** (2013.01)

(58) **Field of Classification Search**

CPC ... G06F 22/006; G01C 22/006; G01C 21/165
USPC 342/461; 703/2, 14
See application file for complete search history.

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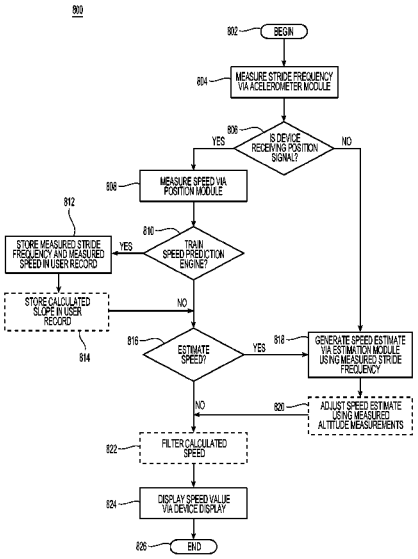
Primary Examiner — Dwin M Craig

(74) *Attorney, Agent, or Firm* — Johnson, Marcou & Isaacs, LLC

(57) **ABSTRACT**

Systems and methods for speed estimation based on stride data using predictive modeling relate to portable wireless devices (**202**) that contain GPS or other location resources to generate position and speed data. The device (**202**) also incorporates an accelerometer (**212**) or other motion sensor. When GPS signals are interrupted, an estimation module (**216**) and associated logic generates a speed estimate based solely on stride frequency data from the accelerometer (**212**). Unlike conventional estimators, the estimation module (**216**) operates on a non-deterministic basis, generating an estimated speed using a joint probability distribution derived from previous speed and stride data captured while positioning signals are available. The estimation module (**216**) can continue to operate when GPS signals are available, and either filter the GPS speed measures for spurious signals, or further train the estimation module (**216**) with new position data. The estimation module (**216**) can also incorporate altitude measurements when estimating speed.

21 Claims, 7 Drawing Sheets



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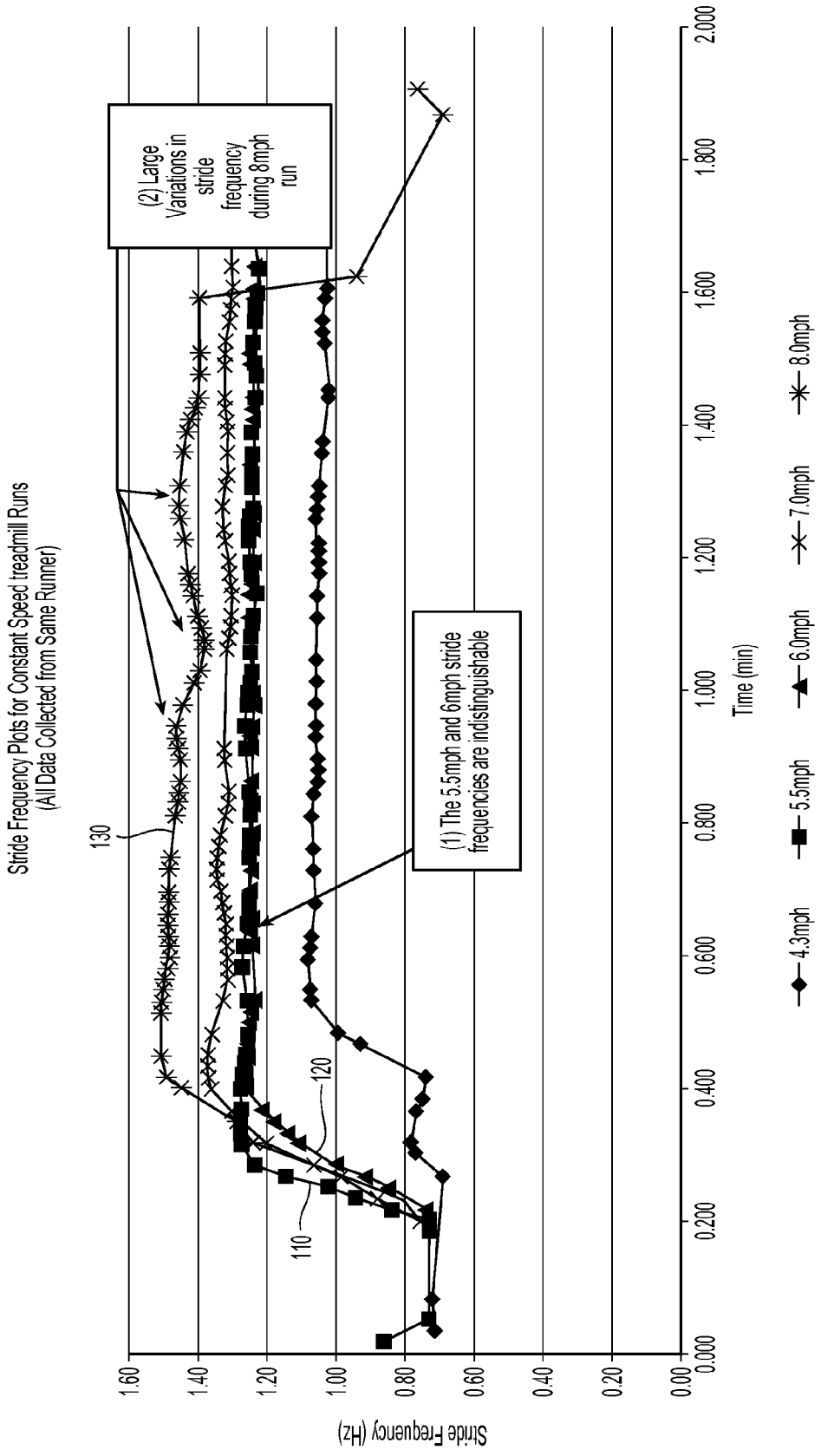
Stride Frequency Plots for Constant Speed treadmill Runs
(All Data Collected from Same Runner)
(2) Large Variations in stride frequency during 8mph run
(1) The 5.5mph and 6mph stride frequencies are indistinguishable
130
120
110
Stride Frequency (Hz)
Time (min)
4.3mph
5.5mph
6.0mph
7.0mph
8.0mph

Fig. 1

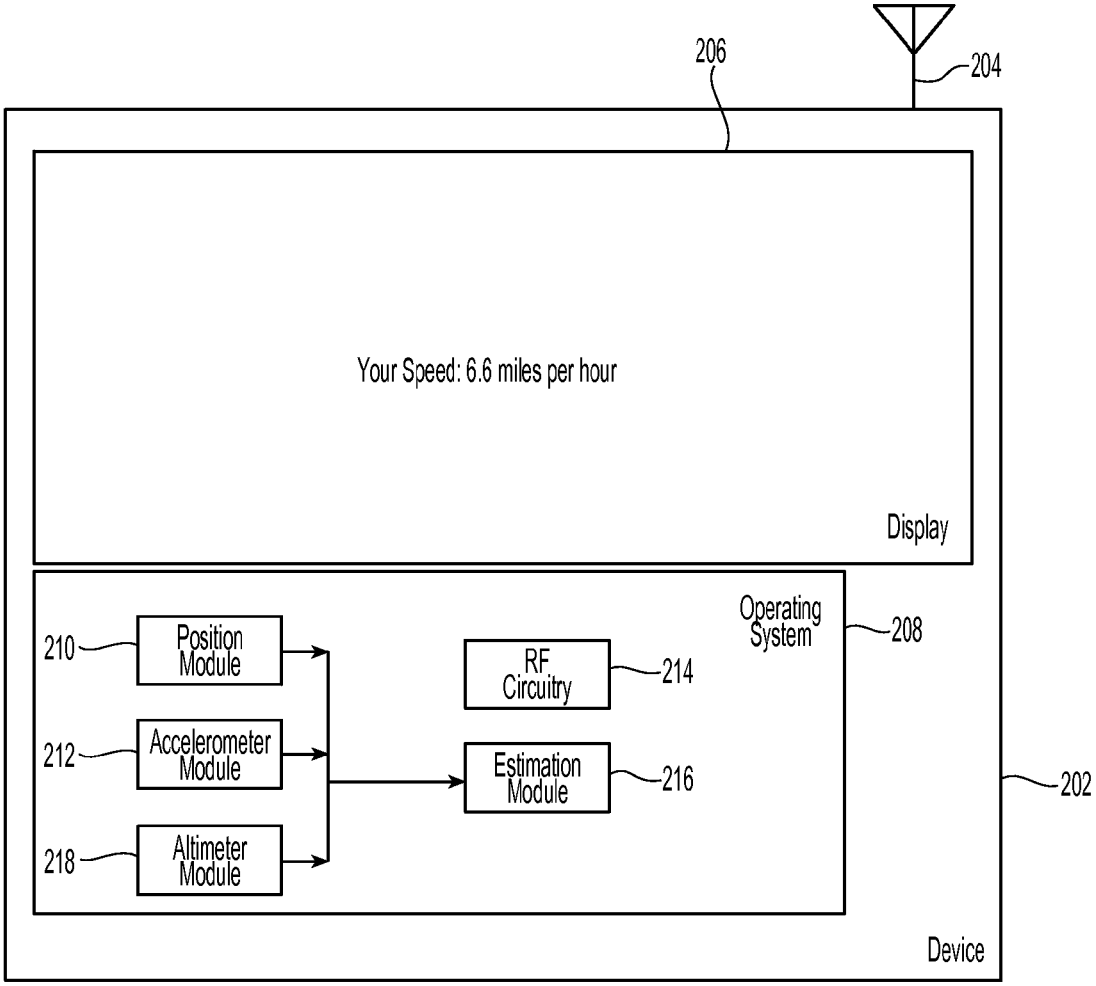
206
204
Your Speed: 6.6 miles per hour
Display
Operating System
208
210
Position Module
212
Accelerometer Module
218
Altimeter Module
RF Circuitry
214
Estimation Module
216
202
Device

Fig. 2

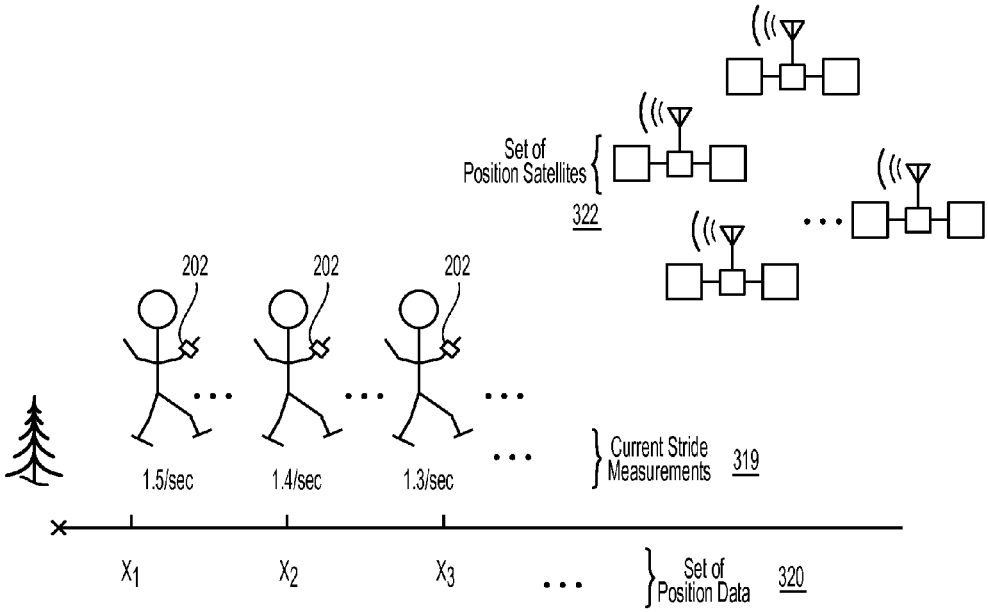
Set of
Position Satellites
322
202
202
202
1.5/sec
1.4/sec
1.3/sec
Current Stride
Measurements
319
X1
X2
X3
Set of
Position Data
320

Fig. 3

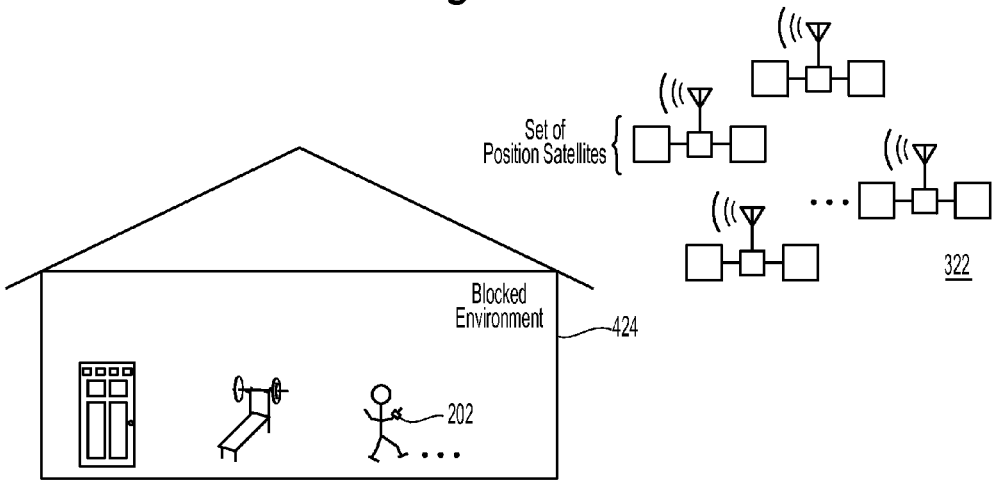
Set of
Position Satellites
322
Blocked
Environment
424
202

Fig. 4

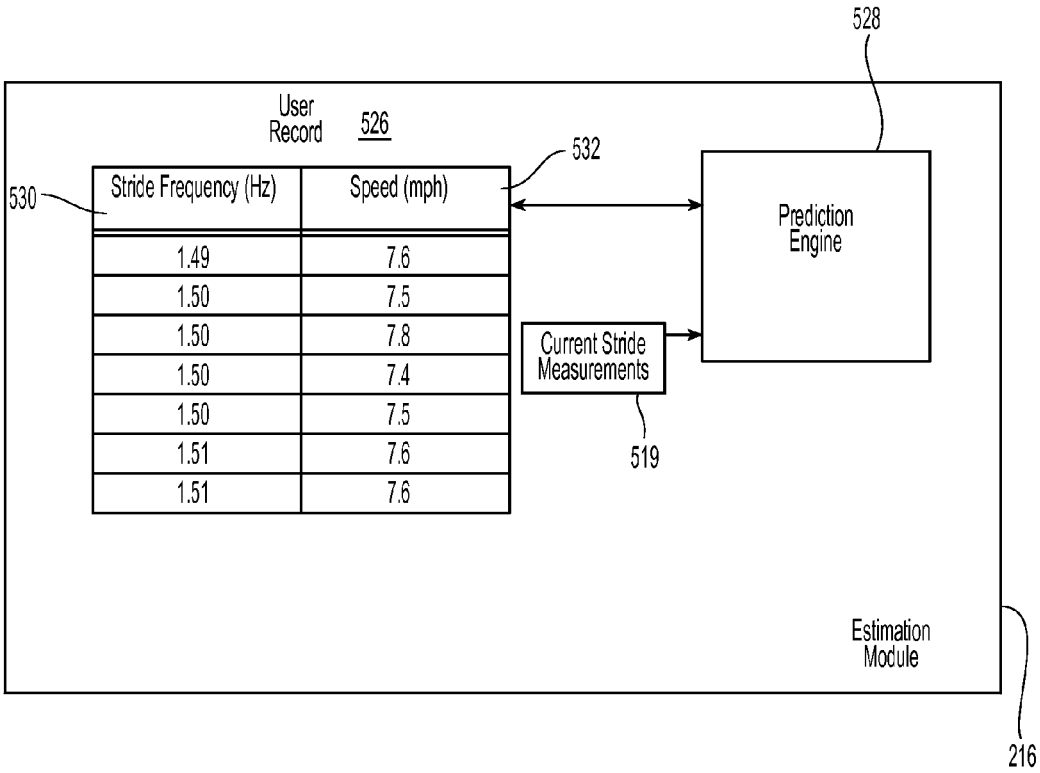
528
User Record 526
532
530
Stride Frequency (Hz)
Speed (mph)
1.49 7.6
1.50 7.5
1.50 7.8
1.50 7.4
1.50 7.5
1.51 7.6
1.51 7.6
Prediction Engine
Current Stride Measurements
519
Estimation Module
216

Fig. 5

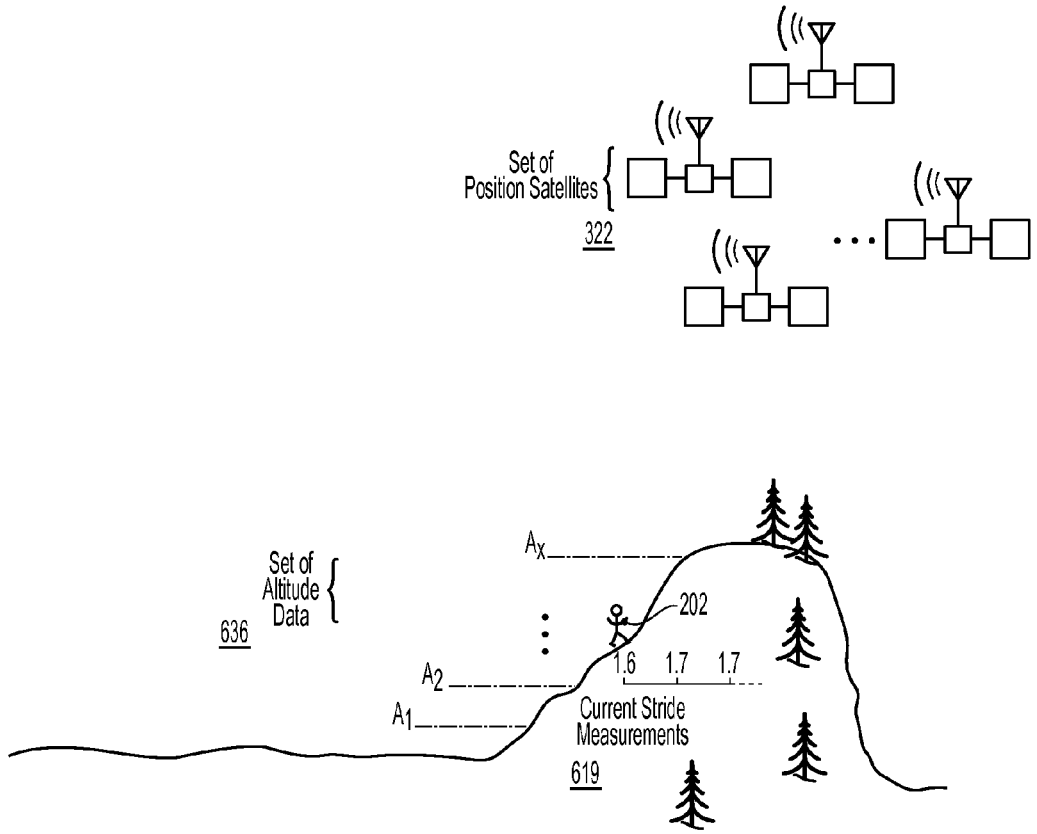
Set of
Position Satellites
322
Set of
Altitude
Data
636
A_x
A_2
A_1
202
1.6
1.7
1.7
Current Stride
Measurements
619

Fig. 6

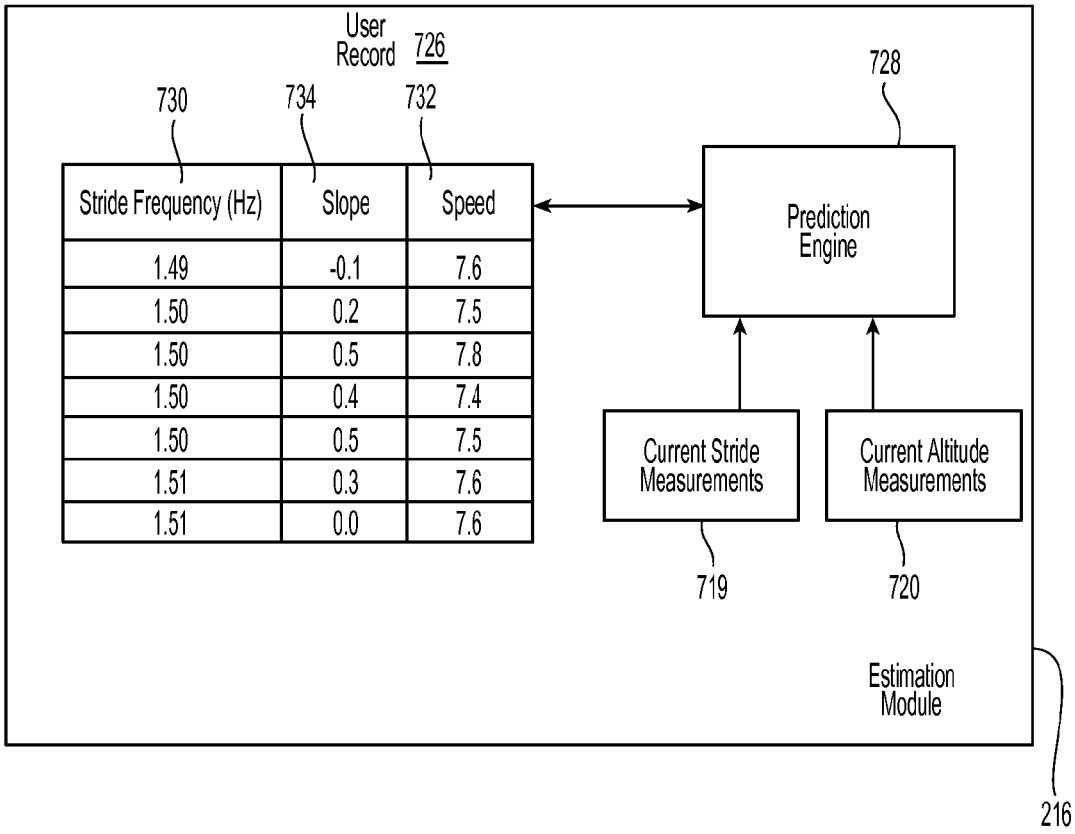
User Record 726
730
734
732
728
Stride Frequency (Hz)
Slope
Speed
1.49
-0.1
7.6
1.50
0.2
7.5
1.50
0.5
7.8
1.50
0.4
7.4
1.50
0.5
7.5
1.51
0.3
7.6
1.51
0.0
7.6
Prediction Engine
Current Stride Measurements
Current Altitude Measurements
719
720
Estimation Module
216

Fig. 7

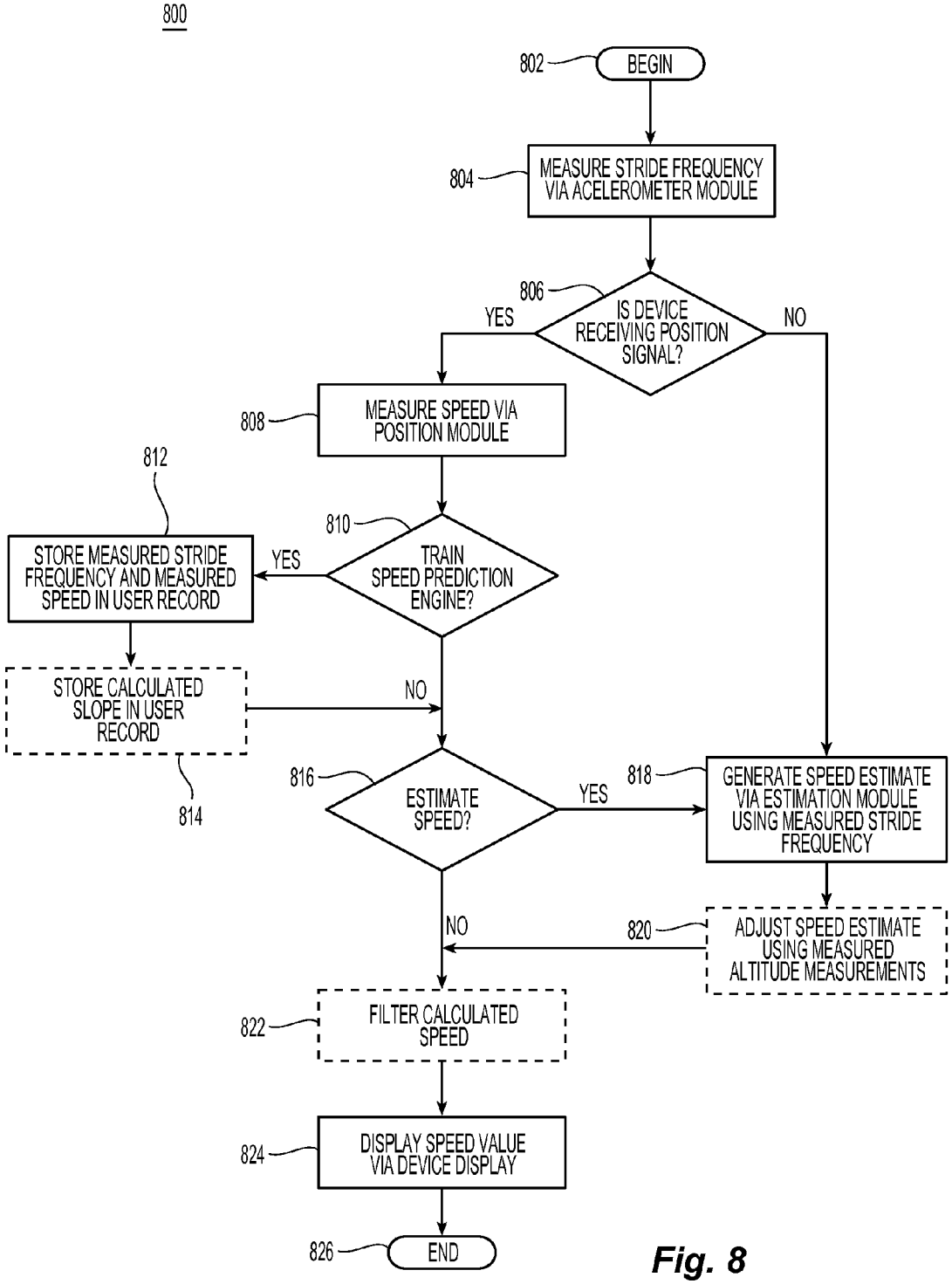
800
802
BEGIN
804
MEASURE STRIDE FREQUENCY VIA ACELEROMETER MODULE
806
IS DEVICE RECEIVING POSITION SIGNAL?
YES
NO
808
MEASURE SPEED VIA POSITION MODULE
810
TRAIN SPEED PREDICTION ENGINE?
YES
812
STORE MEASURED STRIDE FREQUENCY AND MEASURED SPEED IN USER RECORD
NO
STORE CALCULATED SLOPE IN USER RECORD
814
816
ESTIMATE SPEED?
YES
818
GENERATE SPEED ESTIMATE VIA ESTIMATION MODULE USING MEASURED STRIDE FREQUENCY
NO
820
ADJUST SPEED ESTIMATE USING MEASURED ALTITUDE MEASUREMENTS
822
FILTER CALCULATED SPEED
824
DISPLAY SPEED VALUE VIA DEVICE DISPLAY
826
END

Fig. 8

SYSTEMS AND METHODS FOR SPEED ESTIMATION BASED ON STRIDE DATA USING PREDICTIVE MODELING

FIELD

The present teachings relate to systems and methods for speed estimation based on stride data using predictive modeling, and more particularly, to platforms and techniques for estimating a speed value for a user of a device in motion, using nondeterministic speed modeling based on detected stride frequency.

BACKGROUND

In competitive running and other personal recreational applications, portable electronic devices may track the location and speed of a user wearing or carrying the device. In conventional devices of this type, the user's speed while running or performing other activities can often be tracked using positioning platforms, including global positioning satellite (GPS) tracking systems, by dividing elapsed distance by elapsed time. Sometimes, however, signals from GPS satellites can be obscured by trees, buildings, weather, and other obstructions. When GPS signals are corrupted or unavailable, the user will often find it convenient to continue to receive an indication of speed using alternative techniques.

An alternative technique that provides a speed value for a runner or other user detects the stride frequency of that user's walking or running pace. It has been known to use an accelerometer built into a portable electronic device to detect the comparatively sharp acceleration at the start of the user's forward stride. By tracking successive strides, the user's stride frequency can be determined.

In known platforms, the stride frequency can be used as an input to a linear, polynomial, or other deterministic model to generate an estimated current speed of the user's walking or running activity. In known estimators of this kind, the device assumes that the user's speed is related to the frequency of their detected strides in a deterministic or closed-form fashion. Sometimes there are different deterministic models for a walking user and a running user. The deterministic models can be based on human biomechanical models or other calculations which assume a direct correspondence between the stride frequency observed for the user and the user's immediate speed at that stride frequency.

However, empirical use of known speed estimator devices has shown that the estimated speed output obtained from these types of deterministic algorithms does not always match up well with actual speed. A user's estimated speed using deterministic models can differ by forty percent or more when compared to the speed as measured by accurate GPS reception.

There is an opportunity to develop methods and systems for speed estimation, in which an estimation of a user's speed while running or performing other activities can be generated with comparatively high accuracy even when GPS or other location services are not available.

DESCRIPTION OF DRAWINGS

The accompanying drawings, which are incorporated in and constitute a part of this specification, illustrate implementations of the present teachings and together with the description, serve to explain the principles of the present teachings. In the figures:

FIG. **1** illustrates empirical data illustrating the relationship between stride frequency and speed for an exemplary user;

FIG. **2** illustrates a device which can be used in systems and methods for speed estimation based on stride data using predictive modeling, according to various implementations;

FIG. **3** illustrates an environment in which systems and methods for speed estimation based on stride data using predictive modeling can be used to estimate a speed value, according to various implementations;

FIG. **4** illustrates a further environment in which systems and methods for speed estimation based on stride data using predictive modeling can be used to estimate a speed value, according to various implementations;

FIG. **5** illustrates various data tracking and analysis features that can be used in a speed tracking module, according to various implementations;

FIG. **6** illustrates a further environment in which systems and methods for speed estimation based on stride data using predictive modeling can be used to estimate a speed value, including the use of slope data, according to various implementations;

FIG. **7** illustrates various data tracking and analysis features that can be used in a speed tracking module, including the use of altitude or elevation data, according to various implementations; and

FIG. **8** illustrates a flowchart of processing that can be used in speed estimation based on stride data using predictive modeling, according to various implementations.

DETAILED DESCRIPTION

Implementations of the present teachings relate to systems and methods for speed estimation based on stride data using predictive modeling. More particularly, implementations relate to platforms and techniques for estimating the speed of a device worn or carried by a user. The device can be equipped with sensing devices including a location module such as a GPS receiver chip for receiving position data from GPS satellites, as well as an accelerometer module to detect motion data in the device locally. When the GPS signals are obscured and/or at other times, the device can be configured to receive a set of stride data from the accelerometer, and use that data to derive an estimate of the user's speed based on a user record which associates previously captured stride data and previously captured speed data (e.g., calculated by dividing elapsed distance by elapsed time).

Logic within the device can then produce an estimate of the user's current speed based on a non-deterministic engine or model which predicts speed based on the current stride measurement, including stride frequency, and the set of previously captured speed data. In implementations, the predictive model or engine can be or include a Bayesian model or engine, although it will be appreciated that other types of models or engines can be used. The predictive model or engine can be based on a joint probability distribution between previously detected speed data and previously detected stride data, rather than a closed-form calculation.

The accuracy of the estimated speed can be enhanced by the fact that the predictive model is based on the record for that user individually, so that the model captures over time the characteristics of that user's speed behavior as it relates to stride data of that user. The user can thus receive a set of calculated and/or estimated speed data on the device which remains accurate under different operating conditions, including those when regular GPS or other positioning services are not available.

Reference will now be made in detail to exemplary implementations of the present teachings, which are illustrated in the accompanying drawings. Where possible the same reference numbers will be used throughout the drawings to refer to the same or like parts.

FIG. **1** depicts data collected from a single runner performing five separate runs on a treadmill device where each run was at a different, constant speed. The graph of this data shows how stride frequency varied over each run. It may be noted that while known platforms assume there is a closed-form or deterministic relationship between stride frequency and speed, the data shown in FIG. **1** demonstrates that the same stride frequency may result in different actual speeds (lines **110**, **120**), for the same user. The graph in FIG. **1** furthermore demonstrates that the same speed may be achieved at different stride frequencies (line **130**) by the same user. Thus, a deterministic model that matches a particular stride frequency to a unique speed (or stride length, since speed equals stride frequency multiplied by stride length) cannot capture these real-life events when the same stride frequency results in different speeds and when different stride frequencies result in the same speed.

FIG. **2** illustrates a device **202** in which systems and methods for speed estimation based on stride data using predictive modeling can operate. As shown, the device **202** can be configured with hardware, software, firmware, services, and/or other resources to permit the device **202** to calculate speeds related to the motion of the device **202** using a satellite positioning system. Using a sequence of locations and a sequence of elapsed times as determined using the satellite positioning system, the device calculates current speed (e.g., change in distance divided by change in time). Each calculated speed value may be recorded along with a stride frequency at the time period that the speed was calculated. When the satellite positioning system is not available to generate accurate location information, the device **202** estimates speed values using the recorded stride frequency, the recorded speed values, the currently-measured stride frequency, and a non-deterministic model for estimating speed based on the currently-measured stride frequency. Note that the "estimated speed" is not a "calculated speed" in the sense that the estimated speed does not use elapsed distance as a variable, while calculated speed uses elapsed distance and elapsed time as variables.

The device **202** can include a network-enabled communication component, such as, for example, a cellular (3GPP, 3GPP2, LTE) transceiver, a WiFi (IEEE 802.11) transceiver, a WiMAX (IEEE 802.16) transceiver, a Bluetooth (IEEE 802.15) transceiver, an infrared transceiver, and/or other standardized or proprietary communication transceivers and communication buses (such as Ethernet and USB). With such a transceiver, the electronic device **202** can support voice and/or data communications and thus may include a dialing (e.g., telephony) application, a messaging (e.g., email, text messaging, instant messaging) application, a digital media (e.g., MP3, MP4) player application, and/or a data synchronization application.

The device **202** can have a small form-factor such as a watch-style device, an arm-band device, a belt-style device, or a head-set device. As shown, the electronic device **202** can host or incorporate a number of hardware, software, and/or other resources, including a display **206** and an operating system **208**.

The display **206** can be or include a light-emitting diode (LED) display, liquid crystal display (LCD), and/or displays having other types of panels or illumination elements. In some implementations, the display **206** can incorporate hardware-based input components such as, for example, a capacitive or resistive touch-sensitive panel allowing the user to enter data based on touch-points or other actions on the screen. As noted, the device **202** can be configured in a comparatively small form factor, but the touch screen or display screen may be larger for low-vision applications or other use cases. It may be noted that the device **202** can incorporate other input and output components, such as, for example, audio output via a speaker, audio input via a microphone, and/or user input via mechanical buttons or switches.

As shown, the electronic device **202** can host or incorporate further hardware, software, and/or other services or resources to provide an overall framework for operating the device **202** and conducting input, communications, and/or other activity. The resources of the electronic device **202** can include, for example, an operating system **208** installed on the electronic device **202** and controlling the data storage, processing, communications, and/or other resources of the electronic device **202** and/or accessed via the electronic device **202**. The device **202** can incorporate radio frequency (RF) circuitry **214** along with one or more antennas **204**, to conduct wireless signaling with local area networks, wide area networks, positioning systems, and/or other networks, nodes, or stations.

The device **202** can also incorporate resources related to the capture and tracking of speed-related data, including, as illustrated, a position module **210**, an accelerometer module **212**, and an estimation module **216**. In implementations, the position module **210** can be or include a GPS receiver chip, platform, service, and/or module, capable of receiving signals from four or more GPS satellites and translating those signals into comparatively accurate position (e.g., latitude, longitude, and optionally altitude), location, Doppler speed, elevation, time, and/or other data. From the GPS location and time information, the position module **210** can calculate speed by dividing change in location by change in time.

Alternately, in implementations, the speed of the device **202** can be calculated or derived using Doppler speed data determined from a set of GPS carrier signals, rather than from position data. In implementations, the position module **210** can be or include other types or classes of location hardware, software, and/or services, such as location modules based on the known geographic location of cellular towers or their cells, location modules which operate based on radio triangulation techniques, or others. In implementations, for example, the position module **210** can also or instead be based on the Galileo satellite tracking system, and/or others.

The accelerometer module **212** can be or include a hardware, software, and/or other device built into or associated with the device **202**, and configured to detect forces acting on the device **202**, particularly changes in acceleration of the device **202**, and/or other motion phenomena associated with the device **202**. The accelerometer module **212** can be based on piezo-electric, capacitive, strain gauge, and/or other detection or sensor technology. The device **202** can optionally, in implementations, incorporate an altimeter module **218**, such as a barometric altimeter, to sense current altitude values of the device **202**.

In addition, the device **202** can be configured with an estimation module **216** to estimate a speed of the device **202** in the absence of current location information. Data from the position module **210**, the accelerometer module **212**, and the optional altimeter module **218** (when present) can, as shown, be used as input to the estimation module **216** for operations described herein.

The display **206** may show the estimated speed value as determined from the estimation module **216**, the calculated speed value as determined from the position module **210**, or a blend of the two speed values. In implementations, the speed

value (calculated or estimated) can be displayed in miles per hour (as shown), but can also be configured to be displayed in feet per second, kilometers per hour, and/or other units or measures. Pace values, namely minutes per mile or other time over distance values, can also be displayed. In implementations, the display **206** can show a speed value (calculated or estimated) continuously, at regular intervals, upon receiving an input or selection from the user, and/or at other times or under other conditions.

The estimation module **216** and/or other hardware, module, application, and/or service can incorporate processor, memory, logic, software, and/or other resources to estimate speed values and conduct other operations, as described herein.

In one illustrative operating mode, and as for example illustrated in FIG. **3**, the device **202** can be worn, attached to, and/or carried by a user located in a relatively clear or unobstructed environment, such as an outdoor trail, track, and/or other set of surroundings that permit the receipt of signals from at least four position satellites **322**, such as a set of GPS satellites or others. The user can use or operate the device **202** in connection with a variety of activities, including, for example, long distance running events, hiking on public trails, and other athletic, personal recreation, and/or other activities. During those or other activities, the device **202** can generate and capture various data to calculate or estimate a current speed of the user and/or device. That data can include, as shown, a set of current stride measurements **319**, which can be captured using the accelerometer module **212**. The current stride measurements **319** can include a set of stride frequency data, indicating how many strides per second the user of the device **202** is taking. In implementations, the current stride measurements **319** can also or instead include information such as a total number of strides, date and/or time of stride events, and/or other data.

In conditions or environments as shown in FIG. **3**, the device **202** can also capture, generate, and/or receive a set of position data **320**. The set of position data **320** can be received or derived from GPS or other signals received or processed by the position module **210**. The position module **210** can use the set of position data **320** to calculate the current speed value of the device **202**, by comparing the date and/or time stamp values for successive positions, x_1, x_2, x_3, . . . , of the device **202** to the distance between those positions and generate a speed value. In implementations, the current speed value, as measured by the position module **210**, can also or instead be averaged over a predetermined number of position measurements, and/or can be computed using other techniques using the set of position data **320**. It may be noted that the calculated (current) speed data derived from the data produced by position module **210** can be sent to the estimation module **216** to be stored alongside with corresponding (current) stride data **319** from the accelerometer module **212**, for the same time intervals.

According to implementations, it may be noted that while in an unobstructed environment such as illustrated in FIG. **3**, the device **202** can be configured to display the calculated speed as generated by the position module **210**. Speed values that are derived from the set of position data **320** and/or the set of position satellites **322** by position module **210** and/or other modules, logic, and/or software may be referred to at times herein as "calculated" speed values or outputs.

In other surroundings, and as for example shown in FIG. **4**, the device **202** can be located in a blocked environment **424**, such as the interior of a building, inside a gym, under extensive foliage, in densely constructed areas of a city (e.g., "urban canyons"), and/or other locations. In those types of blocked environment **424** or others, the device **202** may be unable to receive, or unable to receive with adequate or consistent signal strength, signals transmitted by the set of position satellites **322**. In those types of operating conditions, the position module **210** may not be able to derive the set of position data **320** and associated information, such as the current calculated speed of the device **202**. In those kinds of situations or others, the device **202** can be configured to switch the way in which the device **202** determines current speed to rely upon current stride measurements **319**, rather than an unavailable set of position data **320**. Speed values that are derived from current stride measurements **319** may be referred to at times herein as "estimated" or "predicted" speed values or outputs.

In those blocked environment operating conditions or others, and as shown for example in FIG. **5**, the device **202** can operate on current stride measurements **519** and other information to generate an estimated current speed. In those cases and others, the estimation module **216** and/or other hardware, module, application, and/or service can access an individual's user record **526**. In implementations, the user record **526** can store a set of previously captured or stored data related to the user's personal activity history and movement. In implementations, the user record **526** can include a set of stored or previous stride frequency data **530** from the accelerometer module **212** and a related set of previously calculated speed data **532** captured at the same time or time interval from the position module **210** for the user of the device. The prediction engine **528** uses probabilistic approaches and this individual's stochastically-related speed and stride history to generate an estimated or predicted current speed based on current stride information **319**, **519**.

In implementations as shown, the estimation module **216** and/or other hardware, module, application, and/or service can incorporate a prediction engine **528** to access the user record **526** and/or other data, and perform speed estimation and other operations. In implementations, the prediction engine **528** can be or include a Bayesian engine or model, in which the set of previous stride frequency data **530** and the set of previously calculated speed data **532** can be used to construct a joint probability distribution of those quantities. The joint probability distribution can relate the stride frequency data recorded during previous activities by the user to calculated speed data with which the user was traveling at those stride frequencies. As the accelerometer module **212** and/or other sensor, detector, application, and/or logic detects new or current stride measurements **519**, the stride measurements **519** can be provided as input to the prediction engine **528** of the estimation module **216**.

Using Bayesian or other prediction models or techniques, the prediction engine **528** and/or other model, engine, logic, application, and/or service can then use the current stride measurements **519** to generate an estimate of the user's current speed based on or derived from the previously calculated speeds **532** which were recorded when prior stride frequency data **530** was equivalent to the current stride frequency measurement. According to implementations, the use of a Bayesian model or engine in the prediction engine **528** will provide a minimum mean squared error estimate of the current speed for a given stride frequency measurement. It will however be appreciated that other modeling techniques, engines, algorithms, and/or calculations can be used.

According to aspects of the present teachings, the use of a prediction engine **528**, rather than a strictly deterministic model or relationship between stride frequency and speed, allows flexibility to account for the non-linear, non-polynomial, or otherwise less than totally predictable correspon-

dence between those variables. Those non-deterministic results can arise, for example, due to the fact that a user may at times reduce his stride frequency, yet increase his speed, by taking longer strides. The same user may increase both stride frequency and stride length during periods of peak exertion, leading to a greater than expected increase in speed. It will be further appreciated that systems and methods according to the present teachings likewise enjoy an advantage in terms of building a model based on the user record **526** that is uniquely tailored to the user's overall activity patterns. This avoids employing deterministic models or relations which assume that a certain walking stride frequency results in a particular speed or that a particular running stride frequency results in a certain speed. This approach is useful because, among other things, experimental data such as that shown in FIG. **1** demonstrates that such assumptions are not always valid, even for the same user.

By applying a prediction engine **528** that is stochastic or non-deterministic in nature, but trained to an individual user, the accuracy of the estimated speeds for that user over a variety of conditions can be increased. Moreover, the prediction engine **528** can evolve or refine the learned model of the user's speed and stride behavior over time, changing as the user's speed patterns change due to age, physical condition, types of activities, and/or other factors.

Thus, and merely for example, consider a scenario in which the accelerometer module **212** and/or other sensor, detector, application, and/or logic detects a current stride frequency of 1.50 Hz (strides per second) given the user record **526** in FIG. **5**. In practice, user record **526** may have thousands of measurements or more, with a plurality of calculated speed measurements for each stride frequency value. In this example, however, user record **526** only contains four calculated speed measurements **532** recorded at a stride frequency **530** of 1.50 Hz. Three of these speeds are different, highlighting the non-deterministic nature of this problem. Possible reasons different calculated speeds may be recorded for a particular stride frequency include error in the accelerometer module **212**, error in the position module **210**, or error in both. Another possible reason for different calculated speeds is that the user may have changed stride length while maintaining a constant stride frequency. For these reasons and possibly others, the stride frequency and calculated speed can be treated as random variables F and V, respectively.

The prediction engine **528** can ameliorate the inaccuracies in the measurements of F and V through a probabilistic approach by generating an estimated speed equal to the expected value of speed for the measured stride frequency of 1.50 Hz, i.e., E[V]F=1.501, given a joint probability distribution generated by the data in user record **526**. Computing the expected value of speed for a given stride frequency narrows the range of possible values from the entire joint probability distribution to a smaller range of values given by the conditional probability distribution of speed for the current stride frequency measurement. Mathematically, the estimated speed $\hat{v}$ is given by

$$\hat{v} = E[V \mid F = 1.50] = \sum_{i=1}^{n} v_i \cdot p\{V = v_i \mid F = 1.50\}$$

where v_i is one of the n unique speeds recorded in user record **526**, and $p\{V=v_i|F=1.50\}$ is the conditional probability that speed v_i was measured when the stride frequency was measured to be 1.50 Hz. Given the user record **526** of FIG. **5** and assuming that it is the entire user record, the following conditional probabilities can be computed: $p\{V=7.4|F=1.50\}=0.25$, $p\{V=7.5|F=1.50\}=0.50$, and $p\{V=7.8|F=1.50\}=0.25$ and the speed estimate is therefore $\hat{v}=(7.4)(0.25)+(7.5)(0.50)+(7.8)(0.25)=7.55$ mph. In practice, the substantially larger amount of data in user record **526** will reduce any gaps in the previous stride frequency data, improve the accuracy of the speed estimation process, and help to reject statistical outliers.

In implementations, if the user continues to be located in the blocked environment **424**, the current stride measurements **319**, **519** can continue to be used to update the estimated current speed value. The display **206** can show the estimated speed determined using the current stride measurements and the probabilistic output generated by the prediction engine **528**.

In implementations, the device **202** can continue to operate in an estimation mode based on current stride measurements **319**, **519** until the device **202** clears the blocked environment and resumes the reception of location signals from the set of position satellites **322**. Upon receiving those location signals, the device **202** can, in implementations, revert to receiving and processing GPS and/or other location signals from the set of position satellites **322**, and switch to displaying those currently measured speed values as determined by the position module **210**, instead of estimated speed values based on the output of the prediction engine **528**. In further implementations, the device **202** can continue to display calculated speed values while simultaneously training the prediction engine **528** by continuing to record current stride frequency and current calculated speed data in the user record **526**, for use in speed estimation at a future time.

In further implementations, the device **202** can be configured to remain in an estimation mode and continue to generate an estimated current speed based on the current stride measurements **319**, even when the device **202** emerges from a blocked environment **424** and begins receiving signals from the set of position satellites **322** again. In operating modes of these types, the device **202** can receive the set of position data **320** at the position module **210**, generate a current calculated speed based on that position data **320**, and use that data and calculated speed to continue to train the prediction engine **528** at the same time that the prediction engine **528** is operating to generate an estimated speed. In operating modes of these types, the prediction engine **528** and device **202** can continue to learn and refine the Bayesian and/or other prediction model, taking advantage of the availability of the set of position data **320** when the device can receive signals from the set of position satellites **322**.

In still further implementations, if a sufficiently large user record has been generated, based on memory usage, number of samples, or some other measure, additional training of the prediction engine **528** may not be necessary and thus the user record **526** may no longer need to be updated. In operating modes of this type, speed estimation can continue to be performed using the current user record **526** without continuing to update user record **526** with the latest stride frequency and calculated speed measurements.

In still further implementations, the device **202** can be configured to operate in a measurement mode using the set of position data **320** when that data is available, and to present the current calculated speed on the display **206** using speed values determined from the set of position satellites **322** when those signals are being received. In such implementations, the device **202** can be configured to perform certain further processing related to speed calculations, and in particular, to filter or condition the position data **320** produced by using the set of position satellites **322**. In such modes or configurations,

the estimation module **216** can receive the set of position data **320**, and calculate a current speed value using that data. In aspects, it may be noted the set of position data **320** received and/or developed from the set of position satellites **322** can be received and processed in real time or near-real time, resulting in a current calculated speed value that can be displayed to the user on an immediate or near-immediate basis.

In modes as noted, before presenting a current calculated speed value to the user, the estimation module **216** and/or other hardware, module, application, and/or service can be configured to perform a data consistency check or operation on the current calculated speed value generated by the set of position data **320**. The speed estimator module **216** and/or other hardware, module, application, and/or service can perform that check by continuing to generate an estimated speed value using the prediction engine **528** using the current stride measurements **319**, **519** and, at the same time, in parallel or conjunction with the calculated speed value derived from the measured set of position data **320** generated by the set of position satellites **322**.

In operation, signals received from the set of position satellites **322** can for example be corrupted due to radio frequency interference of various kinds, leading to a brief set of spurious or anomalous values in the set of position data **320**. The estimation module **216** and/or other hardware, module, application, and/or service, in these filtering modes, can be configured to perform a comparison of the latest or current calculated speed value derived from the set of position data **320** to the latest or current estimated speed value, and determine whether the current calculated speed value calculated from the set of position data **320** deviates by more than a predetermined threshold from the estimated value.

If that calculated speed value exceeds the predetermined threshold, the current value displayed to the user can be temporarily switched to the speed value estimated from the current stride measurements **319**, **519**. Temporary outliers and/or false readings in the calculated speed data can thereby be filtered out and/or avoided. In implementations where the device **202** is also simultaneously training the prediction engine **528** using the current set of position data **320**, the position, speed, and/or other values which deviate by more than the predetermined threshold can likewise be deleted from the data stream used as training sets for the Bayesian and/or other engine.

In certain implementations, the device **202** can also be configured to track and take into account an additional dimension of data when generating the estimated speed of the device **202**. In particular, and as shown in FIG. **6**, the device **202** can be configured to track the change in altitude (i.e., slope) of the device **202** when performing speed determinations, in addition to capturing or processing location, stride frequency, and other variables described previously. As shown in FIG. **6**, the device **202** in such implementations can be configured to capture, store, and track a set of altitude data **636** indicating the altitude of the device **202** above a reference point, such as sea level. In these implementations, the set of altitude data **636** can also be contained in and/or derived from signals received from the set of position satellites **322**, although it will be appreciated that in other implementations, other sources of altitude or elevation data can be used, such as the use of a separate altimeter module **218** in the device **202**, itself. When incorporated in the device **202**, the altimeter module **218** can be or include a barometric-type altimeter device. In implementations, slope values can be calculated from GPS data directly, and the estimation module **216** can use non-GPS altitude data from the altimeter module **218** and non-GPS stride frequency data from the accelerometer module **212**, along with prior distribution data (stride frequency, calculated slope, calculated speed) stored in the user record for the current user, to estimate speed when GPS signals are not available.

In scenarios as shown, the device **202** can also capture a set of current stride measurements **619**, including stride information described above. In aspects, a runner or other user traveling up or down the incline of a mountain, hill, and/or other irregular terrain may alter or adjust their speed and/or stride, based on the severity of the incline, the altitude of the terrain, and/or other factors.

In those kinds of environments or others, a stride frequency model that has been built up for that user in flat terrain may not lead to speed estimation values that remain accurate or fully accurate, due to expected compensations in the user's stride patterns or other physical behavior. As a result, in implementations that are configured to track elevation data, and as shown in FIG. **7**, the estimation module **216** and/or other hardware, module, application, and/or service can be configured to track not just historical stride frequency data **730** and historical speed data **732**, but also historical slope data **734**, where slope data is calculated by dividing change in vertical distance (altitude) by change in horizontal distance. In implementations, as noted, the historical slope data **734** along with any currently received set of altitude data **636** can be received or generated by the position module **210**, operating on signals received from the set of position satellites **322**. In implementations as shown, the user record **726** can record that additional dimension of slope data. Thus, a predictive model may use the prior distribution data for stride frequency, calculated slope, and calculated speed.

When positioning information is not available, the current stride frequency measurement (e.g., as determined using accelerometer module **212**) and the current altitude measurements (e.g., as determined using altimeter module **218**) may be used in conjunction with the predictive model to estimate speed. Initially, the current stride frequency **619**, **719** can be used by the prediction engine **728** as previously described with reference to FIG. **5** to obtain a preliminary estimated speed. This preliminary estimated speed can be converted to an estimated elapsed distance based on the time stamps of the current altitude measurements **720**. Given a change in altitude from the current altitude measurements **720** and the estimated elapsed distance, the prediction engine **728** can calculate a current (estimated) slope value. With the current stride measurements **719** and the current slope value, the prediction engine **728** can use the augmented user record **726** to generate an estimated speed based on both the current stride measurements **619**, **719** and the current altitude measurements **720** as follows: $\hat{v}; =E[V|F=f, \Theta=\theta]$ where $\hat{v}$ is the estimated speed, F, Θ, and V are the random variables of stride frequency, slope, and speed, respectively, and f and θ are the measured stride frequency and the current (estimated) slope value, respectively.

In implementations, the slope value can also or instead be estimated from the current altitude measurements **720** in a recursive fashion using the last slope and speed estimates produced by the prediction engine **728**. In that case, the prediction engine **728** can estimate a horizontal displacement in the current sampling period by multiplying the horizontal speed by the duration of the current sampling period. The prediction engine **728** can then combine the estimated horizontal distance with the change in altitude during the current sampling period to produce an estimate of the current slope. In recursive implementations of this type, during initial conditions when no previous speed or slope values have been stored, the current stride frequency and an estimated slope of

zero can be passed to the prediction engine **728**, to begin computation. As noted, implementations incorporating slope values can be advantageous in hilly or mountainous terrain, and in other environments.

FIG. **8** illustrates a flowchart **800** of speed determination and other processing that can be performed in systems and methods for speed estimation based on stride data using predictive modeling, according to aspects. In step **802**, speed estimation processing can begin. In step **804**, the current stride frequency can be measured from the accelerometer module **212**.

In step **806**, a determination can be made whether the device **202** is receiving a position signal from the set of position satellites **322** via the position module **210**. If the determination of **806** is yes, processing can proceed to step **808**, otherwise processing can proceed to step **818**. In step **808**, the current calculated speed for the device **202** can be measured from the position module **210**. In step **810**, a determination may be made whether to train the speed prediction engine **528**, **728**. If the determination in step **810** is yes, processing can proceed to step **812**, otherwise processing can proceed to step **816**. In step **812**, the current stride measurements **319** and the calculated speed are added to the user record **526**, **726**. In optional step **814**, in implementations in which current altitude measurements **720** are used, the calculated slope can likewise be stored in the user record **526**, **726**.

In step **816**, a determination can be made whether to estimate the current speed, or to use the currently calculated speed. If the determination in step **816** is yes, processing can proceed to step **818**, otherwise processing can proceed to step **822**. In step **818**, a speed estimate is generated in the estimation module **216** using the current stride measurements **319**, **619**, which can be or include currently measured stride frequency values as detected by the accelerometer module **212**. In optional step **820**, in implementations using slope data and/or altitude data as described above in connection with FIGS. **6** and **7**, the estimation module **216** can generate or adjust a speed estimate using the current altitude measurements **720**, related slope values, or associated information. In step **822**, the calculated speed can be filtered using the estimated speed, as an optional step. In step **824**, the speed (either the calculated speed or the estimated speed) is displayed on display **206** of device **202**. The speed estimation process ends in step **826**. It may be noted that in implementations, the process illustrated in FIG. **8** can be executed for more than one user and/or at more than one time, for example at different times while the device **202** is being operated by different users, and results can be stored to one or more user record **526**, **726**.

It will be appreciated that while various processing activity, logical decisions, and/or other operations illustrated in FIG. **8** have been described as taking place in steps, that two or more of various of those operations or activities can be combined into one operation or activity, and that any one or more of those operations or activities can be divided into two or more operations or activities. Moreover, while those various operations or activities have been illustrated and described as occurring in a certain order, it will be appreciated that in implementations, those same and/or other operations or activities can take place in a different order or orders. Further, while various operations or activities have been described as being carried out by certain hardware, software, service, and/or other resources, it will be appreciated that in implementations, the same activities and/or operations can be carried out by other hardware, software, service, and/or other resources.

In implementations, it may be noted that the device **202** can comprise a number of hardware, software, firmware, communications, and/or other resources including a processor communicating with memory, such as electronic random access memory, operating under control of or in conjunction with an operating system, such as a mobile device operating system, which can host an application programming interface (API) and/or other components or resources. The processor can be incorporated in one or more microprocessors, microcontrollers, chips, servers, clusters, and/or other computers or hardware resources, and/or can be implemented using cloud-based resources. The RF circuitry **214** contained in the device **202** can be or include a transceiver, a modulator/demodulator, and other circuits. The device **202** can host further software including one or more applications, such as communications, messaging, texting, telephony, browser, and/or other applications or services. The device **202** can further host a data store, such as a database stored on a local solid state or other memory, to access or store position data, speed data, altitude data, Doppler data, stride data, and/or subsets of selections thereof, along with other content, media, or other data. Other configurations of the device **202**, associated radio frequency hardware or software, network connections, and other hardware, software, and service resources are possible.

As used herein, each of a "model," a "module," and an "engine" can be or include hardware, software, firmware, logic, a self-learning network, and/or service resources, in any combination. Each of those entities can operate under software or other programmed control.

The foregoing description is illustrative, and variations in configuration and implementation may occur to persons skilled in the art. For example, while implementations have been described in which the device employs a single estimation module **216** and single prediction engine **528**, **728**, in implementations, more than one module can perform the same operations of those engines, models, and/or modules. Similarly, while implementations have been described in which the estimation module **216** and/or other hardware, module, application, and/or service accesses the user record **526**, **726** of one user, in implementations, the device **202** can host the user records of multiple users. Other resources described as singular or integrated can in implementations be plural or distributed, and resources described as multiple or distributed can in implementations be combined. The scope of the present teachings is accordingly intended to be limited only by the following claims.

The invention claimed is:

1. A method of processing data, comprising:

receiving a stride frequency measurement at a portable device;

accessing a predictive model based on a nondeterministic association between a previous set of stride frequency data and a previous set of calculated speed data at corresponding time intervals; and

generating an estimated speed value based on the stride frequency measurement and the predictive model.

2. The method of claim **1**, wherein the nondeterministic association comprises a joint probability distribution between the previous set of stride frequency data and the previous set of calculated speed data.

3. The method of claim **1**, wherein the predictive model comprises a Bayesian model.

4. The method of claim **1**, further comprising:

capturing a current set of position data at a current set of time data in the portable device; and

generating a current calculated speed value based on the current set of position data and the current set of time data.

5. The method of claim 4, wherein capturing a current set of position data at a current set of time data comprises at least one of:

receiving a set of global positioning system (GPS) data, a set of Doppler data, or a set of cellular triangulation positioning data.

6. The method of claim 4, wherein capturing a current set of position data at a current set of time data comprises:

receiving a set of Doppler data.

7. The method of claim 6, further comprising:

filtering the current calculated speed value based on the estimated speed value.

8. The method of claim 4, further comprising:

filtering the current calculated speed value based on the estimated speed value.

9. The method of claim 4, further comprising:

recording the stride frequency measurement;

updating the predictive model based on the current calculated speed value and the stride frequency measurement.

10. The method of claim 1, wherein generating an estimated speed value comprises:

automatically generating the estimated speed value based on the stride frequency measurement when a current set of position data is unavailable.

11. The method of claim 1, wherein accessing a predictive model comprises:

accessing a predictive model associated exclusively with an individual user of the portable device.

12. The method of claim 1, wherein the predictive model is also based on a previous set of slope data.

13. The method of claim 12, wherein the estimated speed value is generated based on the stride frequency measurement, a current slope value, and the predictive model.

14. A device, comprising:

an accelerometer module; and

a processor, communicating with the accelerometer module, the processor being configured to

receive a stride frequency measurement from the accelerometer module,

access a predictive model based on a nondeterministic association between a previous set of stride frequency data and a previous set of calculated speed data at corresponding time intervals, and

generate an estimated speed value based on the stride frequency measurement and the predictive model.

15. The device of claim 14, further comprising:

a position module; and

wherein the processor is further configured to

receive a current set of position data from the position module, and

generate a current calculated speed value based on the current set of position data.

16. The device of claim 15, wherein the position module comprises:

a global positioning system (GPS) module or a cellular triangulation positioning module.

17. The device of claim 15, wherein the processor is further configured to update the predictive model based on the current calculated speed value and the stride frequency measurement.

18. The device of claim 14, further comprising:

an altimeter module coupled to the processor,

wherein the processor is configured to generate a slope measurement and the predictive model is also based on a previous set of calculated slope data.

19. The device of claim 18, wherein the estimated speed value is generated based on the stride frequency measurement, the slope measurement, and the predictive model.

20. The device of claim 14, further comprising:

a position module; and

wherein the processor is further configured to generate a current calculated speed value based on received Doppler data.

21. The device of claim 14, further comprising:

a display, coupled to the processor, configured to annunciate the estimated speed value.

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